ELECTROMAGNETIC SENSOR ARRAYS--
EXPERIMENTAL STUDIES

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INTRODUCTION

The objectives of this research program are to develop the theoretical models, design methodology, and technology needed for the optimum application of near-field electromagnetic sensor arrays in NDE and robot control. A basic requirement for this work is to be able to analyze and control the spatial-frequency content in the field configuration generated by the array. To aid in understanding how best to satisfy this requirement, initial efforts at SRI have focused on obtaining experimental measurements of the relative spatial distributions associated with the responses of eddy-current reflection probes to surface steps and surface-breaking rectangular slots in aluminum plates. This paper presents the results obtained using a commercial reflection probe (Nortec SPO-2065) and an SRI-constructed five-coil, air-core reflection probe to interrogate such surface discontinuities. The data obtained with the five-coil probe are then compared with the results of a theory for the spatial response of such a probe that has been developed at Stanford University [1].

MEASUREMENT SYSTEM

We have built an automated system for acquiring the amplitude and phase of a sensor array's output voltage as the array is scanned in a plane (x and y) under computer control (Fig. 1). The sensor array (or work piece) can be stepped along in raster fashion in minimum increments of 0.002 in. (or multiples thereof). A Nortec NDT-18 eddyscope is used as source and receiver, and the digitized data are stored on magnetic tape for off-line processing. The NDT-18 eddyscope is an analog instrument containing a synthesized source that can be tuned from 50 Hz to 5 MHz and can be used with reflection probes as well as with absolute and differential probes. Software has been developed for displaying the data in several ways, including perspective plots and contour plots.

STEP RESPONSES OF A REFLECTION PROBE

We used a Nortec SPO-2065 to investigate the relative step responses of a reflection-type probe. The drive coil in this probe has about a

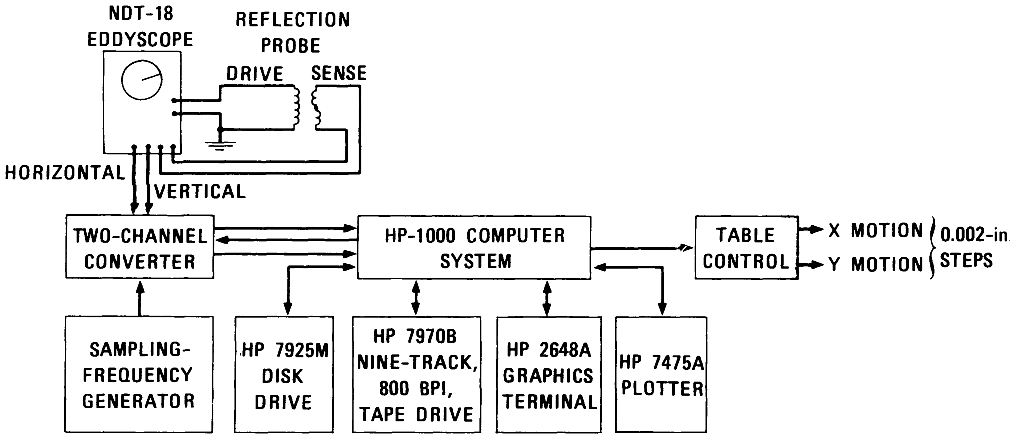

Fig. 1. Data acquisition system.

0.1-in. outer diameter. The sensor array is composed of a differential pair of small D-shaped coils located side by side within the inner diameter of the drive coil. Based on the dimensions of these sense coils, a spatial resolution of about 0.040 in. would be expected for this probe. (This resolution length corresponds to a spatial frequency of 25 in.^{-1}, or 1.0 mm^{-1}.)

The probe's measured amplitude and phase responses to a series of 0.004-in.-deep steps milled in an aluminum plate are shown in Fig. 2. Each step in the plate was 0.1 in. wide. Twenty scans were taken to produce the perspective plots that are shown, although in this case, of course, the output voltages produced by each scan are identical (except for a small amount of backlash between scans). The amplitude response illustrates two of this probe's resolution characteristics: (1) each step is resolved along the scan line, as expected, and (2) the variation of the vertical distance of each step from the probe is also easily resolved. In the experiment, this vertical distance varied between 0.004 and 0.016 in. (0.004 in. of lift-off occurred outside the step region). Generally, without resorting to any data processing, the distance over which vertical resolution is obtained should be about equal to the transverse resolution of the sensor array, an assertion that is borne out by these data.

One objective of SRI's work in this area will be to develop data-processing algorithms that enhance the spatial resolution of sensor arrays. Although the phase response shown in Fig. 2 is not very informative as it stands, phase data are expected to be an essential input to a resolution-enhancing algorithm.

A reflection probe in which the drive and sense coils are essentially coplanar* is linearly polarized; that is, the probe's step response is a maximum when the scan direction is perpendicular to the edge of the step and aligned with a line that passes through the centers of the sense coils

*In some reflection probes, the coils are coaxial.

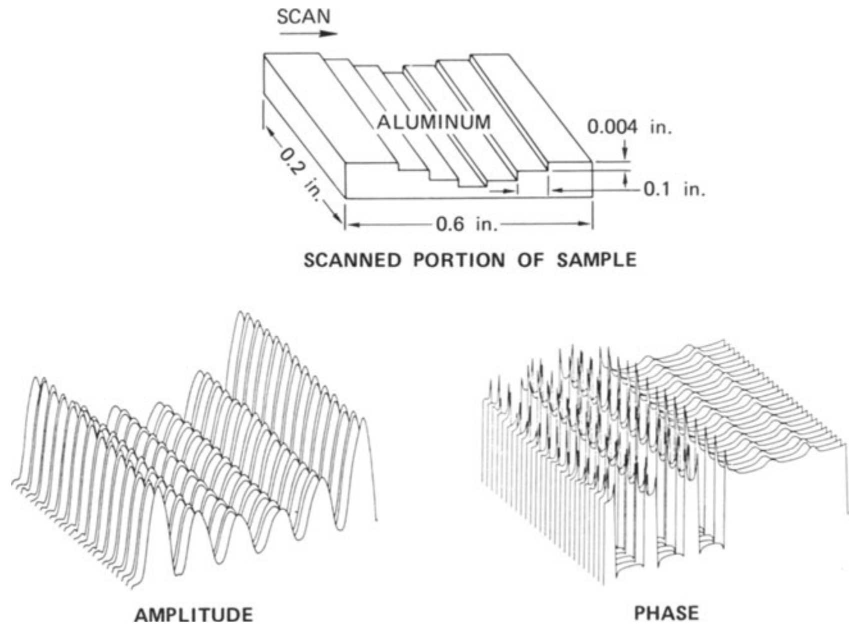

Fig. 2. Stairstep response of a reflection probe.

(parallel polarization), and it will be a minimum (ideally zero) when the probe is rotated by 90° (perpendicular polarization).

The response of the Nortec reflection probe to a curved step illustrates this polarization-dependent behavior (Fig. 3). The important implication of this characteristic of reflection probes is that, by combining data sets from both polarizations, the direction of the edge (or the orientation of a crack) with respect to the scan direction can be estimated. Thus, for example, by feeding this information back to the scan controller, the sensor array could be made to follow an edge.

TEST RESULTS FOR A FIVE-COIL PROBE

To provide both polarizations in a single probe, a five-coil, air-core reflection probe was designed at Stanford University and fabricated at SRI. The coils were made relatively large to minimize construction difficulties. The cross section of this probe is shown in Fig. 4. The outer diameter of the drive coil is 0.67 in., and the outer diameter of each sense coil is 0.19 in. The distance between the centers of diametrically opposed sense coils in 0.28 in. The drive coil consists of 24 turns of #34 copper wire, while each sense coil contains 54 turns. This number of turns results in a height for the drive coil of 0.05 in.; the height of each sense coil is 0.10 in. At 500 kHz, the measured input impedance of the drive coil resting on aluminum is 6.3 + j17.4 Ω, and the corresponding impedance of a differential pair of sense coils is 5.6 + j39.6 Ω, values that are compatible with the source and detector impedances in the NDT-18.

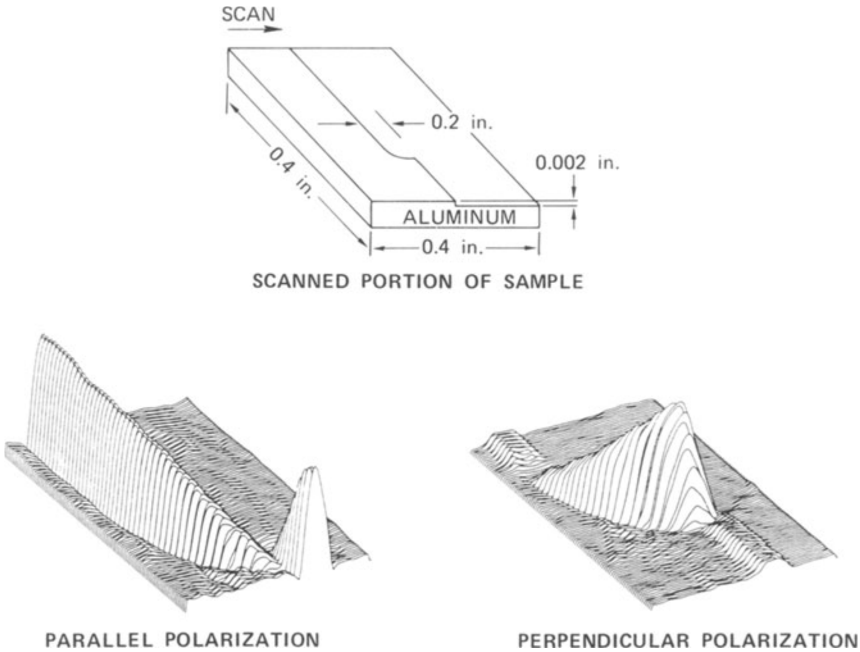

Fig. 3. Response of a reflection probe to a curved step.

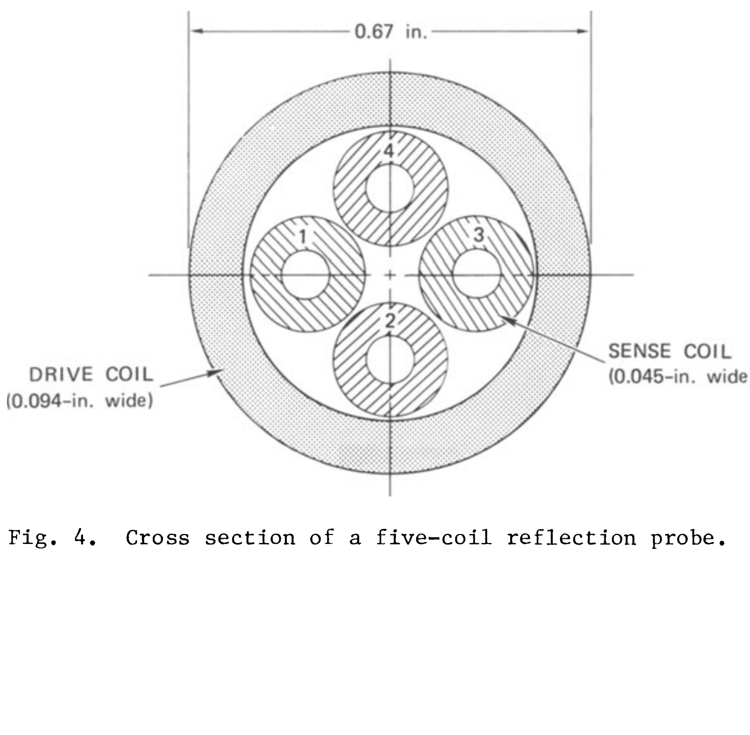

Fig. 4. Cross section of a five-coil reflection probe.

As can be seen in Fig. 4, this probe contains four coils in its sensor array. However, in experiments carried out to date, only two of the sense coils have been operative at any one time. In particular, diametrically opposed coils have been connected as a differential pair.

For one experiment, three slots of differing depths were milled into an aluminum plate. These slots were placed side by side, 1 in. apart. The slots were all 0.125-in. wide and 1.5-in. long. Figure 5 shows the results of scanning across these slots with the five-coil probe (only one sensor pair active). The perspective plot of the results obtained by scanning across the 0.250-in.-deep slot shows a typical differential-probe response in the x-direction and a typical absolute-probe response in the y-direction. This behavior is the result of the linear polarization characteristic discussed above. Stated another way, the x-response is determined by the spatial frequencies associated with the sensor array, while the y-response is determined by the spatial frequencies associated with the drive coil.

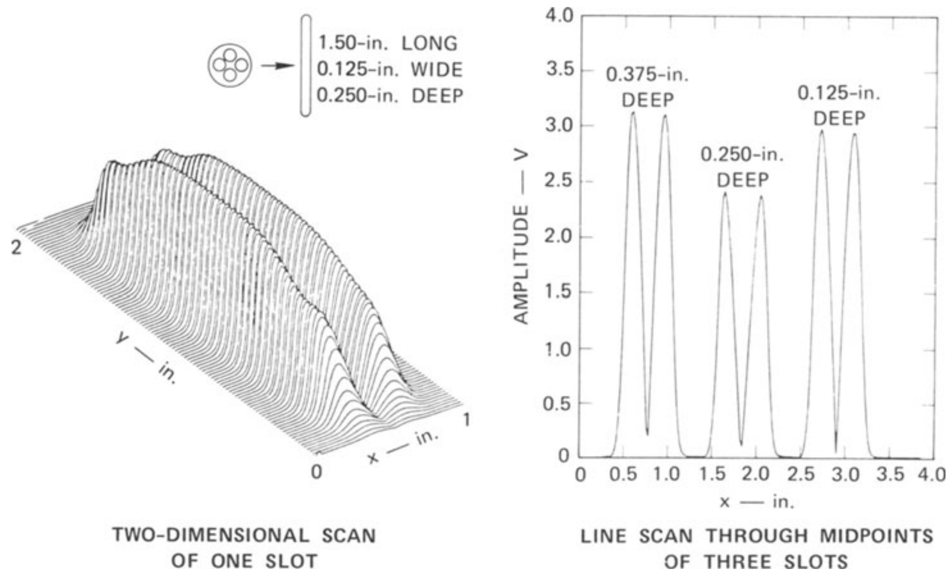

Fig. 5. Slot response of five-coil reflection probe--500 kHz.

The line scan through the midpoints of these slots illustrates both the transverse resolution and the depth resolution of this probe. The transverse resolution appears to be about ±0.125 in., and the depth resolution rapidly deteriorates for depths greater than 0.125 in. These numbers are consistent with the dimensions of the probe. As mentioned previously, one objective of future work will be to develop data processing techniques for improving the image quality produced by such a sensor array.

A second experiment was conducted to obtain data for comparison with theoretical results computed at Stanford University [1]. In this experiment, the five-coil probe was used to make a series of five perpendicular scans across a 0.004-in. step in an aluminum plate. The orientation of the probe differed in each scan; starting from the point at which the line through the centers of the differential pair of sense coils was aligned with the scan direction (designated 0°), the probe was rotated in steps of 22.5° through 90° (designated 90°).

The experiment results are shown in Fig. 6. As expected, the maximum measured step response is obtained at 0°, and the response decreases as the probe is rotated toward 90°. Comparisons with theory are shown for probe orientations of 0° and 67.5°. Since the NDT-18 is an uncalibrated instrument, the theoretical and experimental data were matched at the maximum of the 0° scan. With this single-point calibration, the shapes of the main theoretical and experimental step responses are seen to agree well, and the peak amplitudes of the 67.5° responses are in excellent agreement. The minor differences between theory and experiment outside the main step-response region are thought to be due to an interaction between the step and the drive coil that is not included in the theory.

SUMMARY

In summary, as a first step in our development of electromagnetic sensor arrays, we have made a number of relative measurements of the responses of two-element sensor arrays (reflection probes) to steps and slots in aluminum plates. These measurements have demonstrated the basic spatial characteristics of such arrays and have been used successfully to validate a theoretical model for a reflection probe.

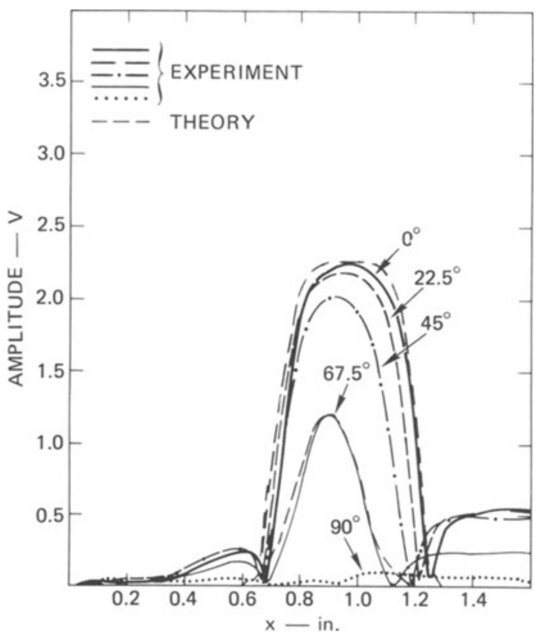

Fig. 6. Step response as a function of probe orientation relative to the edge--500 kHz.

Our future plans include evaluating candidate technologies for fabricating complex sensor arrays with small elements, designing and testing an electronically scanned linear array, and developing imaging algorithms for such arrays.

ACKNOWLEDGMENT

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REFERENCES

[1] B. A. Auld, J. Kenney, and T. Lookabaugh, "Electromagnetic Sensor Arrays-Theoretical Studies," these Proceedings.

DISCUSSION

Mr. Clayton Teague (NBS): I was curious if you have tried to use these techniques for looking at burrs along edges?

Mr. Auld: Burrs? Not yet.

Mr. Teague: It looks like that would be an interesting possibility. Detecting and locating burrs is a very common manufacturing technology problem, and it looks like you have very great sensitivity to the characteristics of edges.

Mr. Auld: Yes.

From the floor: What's the minimum step size you can resolve?

Mr. Bahr: In our table, we have a 2-mill step size.

From the floor: You haven't tried to see how small a step you could actually detect?

Mr. Bahr: Oh, you mean the step at the edge?

Mr. Bahr: We have looked at edge steps on the order of 2 to 4 mills with no problem, but we haven't gone to smaller steps than that.

Mr. Buckley: Yes.

Mr. H. K. Wickramasinghe (IBM): With what accuracy do you think you could track an edge?

Mr. Bahr: That depends on the spatial extent of the probe array and we haven't worked out a complete quantitative evaluation of that yet.

Mr. Wickramasinghe: That accuracy must depend on the distance you are away from the edge.

Mr. Bahr: Yes, However we don't yet have any accuracy number. That's a parameter that would be under our control to a great extent because of the increased degrees of freedom provided by an array of sensors.

Mr. Wickramasinghe: But the accuracy would get worse the further away you got from the edge.

Mr. Bahr: Presumably. It will depend on how well we are able to do in the focusing of the array.

From the floor: Were you using air-core probes or another type?

Mr. Auld: Air-core probes.